Applied Thermal Engineering 75 (2015) 445–450

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Combustion behaviour of pulverised coal in high temperature air condition for utility boilers

Masato Tamura [a,*], Shinji Watanabe [a], Kenichirou Komaba [a], Ken Okazaki [b]

[a] Combustion Engineering Department, Engineering Centre, IHI Corporation, 1-1, Toyosu 3-chome, Koto-ku, Tokyo 135-8710, Japan
[b] Department of Mechanical and Control Engineering, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8550, Japan

HIGHLIGHTS

- Novel burner can realise both conventional and HTAC mode without any unstable.
- HTAC can be established with a combustion air temperature as low as 185 °C.
- Substantial NO_x reduction can be achieved under HTAC mode.

ARTICLE INFO

Article history:
Received 7 February 2014
Accepted 22 September 2014
Available online 2 October 2014

Keywords:
HTAC
MILD combustion
Pulverized coal combustion
Burner
NO_x reduction

ABSTRACT

High Temperature Air Combustion technique (HTAC) is expected to improve the combustion efficiency and NO_x emissions of fossil fuels. This paper presents the results from experimental measurements under steady combustion mode conditions and during the change from conventional air combustion mode to HTAC mode of a newly proposed burner configuration. A 1.2 MWth pulverised coal fired furnace has been used to evaluate the characteristics of HTAC and conventional combustion. To realise both the HTAC and the conventional modes, is one of the important HTAC technological tasks for practical use in utility boilers. During the start-up process, HTAC operation mode cannot be achieved because the air for combustion is still cold. Therefore burner configurations for both modes, conventional and HTAC, are required. In this study, a new burner is proposed and the start-up procedure of pulverised coal fired boilers adopting HTAC is demonstrated. The newly proposed HTAC burner enables successful operation mode switching in both ways between conventional and HTAC modes.

The study shows that HTAC can achieve NO_x reduction whilst maintaining sufficiently high combustion efficiency. The flat and high in-furnace temperature suggests a possibility of being able to use a smaller boiler furnace.

1. Introduction

Reduction of environmental impact and improvement of plant efficiency are essential in coal fired power stations. Air staging is a well-known technique for NOx reduction and has been studied by various researchers [1–3]. It was concluded that residence time and stoichiometric ratio in the primary combustion zone have a strong effect on NO_x emissions. Over the past two decades, the technology of high temperature air combustion (HTAC) has been developed and researched as a clean and highly efficient process for pulverised coal combustion. HTAC technology is also referred to as Excess Enthalpy Combustion, Flameless Oxidation or Mild combustion [4–8]; it has already been applied to industrial furnaces and heating furnaces [9,10]. A typical way of high temperature air generation is to use a regenerative heat exchanger [11]. This is where flue gas and air supply directions are frequently changed for heat storage and release; fuel supply also has to be switched at the same timing. This fuel switching is the most difficult problem in the application of HTAC in pulverised coal firing. There is a grinding process for producing pulverised coal, causing time lags in the order of several minutes. The indirect firing system (bin storage system) can be applied for avoiding the lag due to grinding, but even in this case a time lag remains due to the distance between coal feeder and burner. The measure proposed here is to generate high temperature air continuously and thereby realise HTAC of pulverised coal without the need of fuel switching. It is suggested to

* Corresponding author. Tel.: +81 3 6204 7528; fax: +81 3 6204 8790.
E-mail address: masato_tamura@ihi.co.jp (M. Tamura).

http://dx.doi.org/10.1016/j.applthermaleng.2014.09.059
1359-4311/

mix high temperature flue gas with secondary combustion air to produce a hot combustible mixture of low oxygen content. The concept of this process is shown in the paper by Wünning et al. [5].

There is a large amount of research on pulverised coal [12–19]; however, they are focused on combustion characteristics such as NO_x emissions and burnout. To the authors' knowledge there is no study which is attributed to the burner start-up process.

Suda et al. [12] evaluated the combustion characteristics of pulverised coal in HTAC and obtained significant ignition improvement and decrease of NO_x emissions. Kiga et al. [13] also confirmed that combustion with high temperature air can reduce NO_x emission and improve burnout efficiency. Weber et al. [14] examined the MILD combustion of natural gas, heavy and light oils, and pulverised coal in highly preheated air using a 0.58 MWth furnace. They found that the temperature and concentration fields were uniform, and claimed a high NO_x reduction potential. Li et al. [15] investigated the characteristics of MILD oxy-combustion and air combustion of light oil and pulverised coal in 0.3 MWth pilot-scale furnace. In their experiments, the burnout had generally been poorer for the MILD combustion than the conventional combustion. Stadler et al. [16] investigated the MILD combustion of pulverised coal in various oxidising atmospheres such as air, Ar/O_2 and CO_2/O_2. They showed that there is a potential for reduction of O_2 concentration with MILD oxy-combustion. Mancini et al. [17] performed CFD for evaluation of HTAC technology implementation to pulverised coal boilers. As reviewed above, many researchers have investigated HTAC of pulverised coal, but little research considers an actual boiler operation. Early establishment of HTAC mode in the start-up process yields NO_x reduction for a longer period of operation.

In this research, a new burner is proposed to apply HTAC technology to the pulverised coal fired boiler. In the present experimental work, the performance of a HTAC burner is tested which allows both conventional and HTAC modes. To confirm the applicability of HTAC technology, temperature and oxygen concentration are set lower than in previous studies. The mode switching from conventional to HTAC mode will be demonstrated in Section 3.1. NO_x and burnout are measured to investigate the influence of staged air supply on performance in HTAC mode (Section 3.2). Finally, the temperature distribution within the furnace is examined in Section 3.3.

2. Experimental

2.1. Experimental setup

The combustion experiments are carried out in a bench-scale furnace whose maximum firing rate of pulverised coal is 150 kg/h. The schematic flow diagram is shown in Fig. 1. The furnace has an inner diameter of 1.3 m and is 7.5 m long. It is equipped with refractory-lined fire bricks and a water-cooled jacket with observation ports along the furnace axis. Secondary air can be supplied

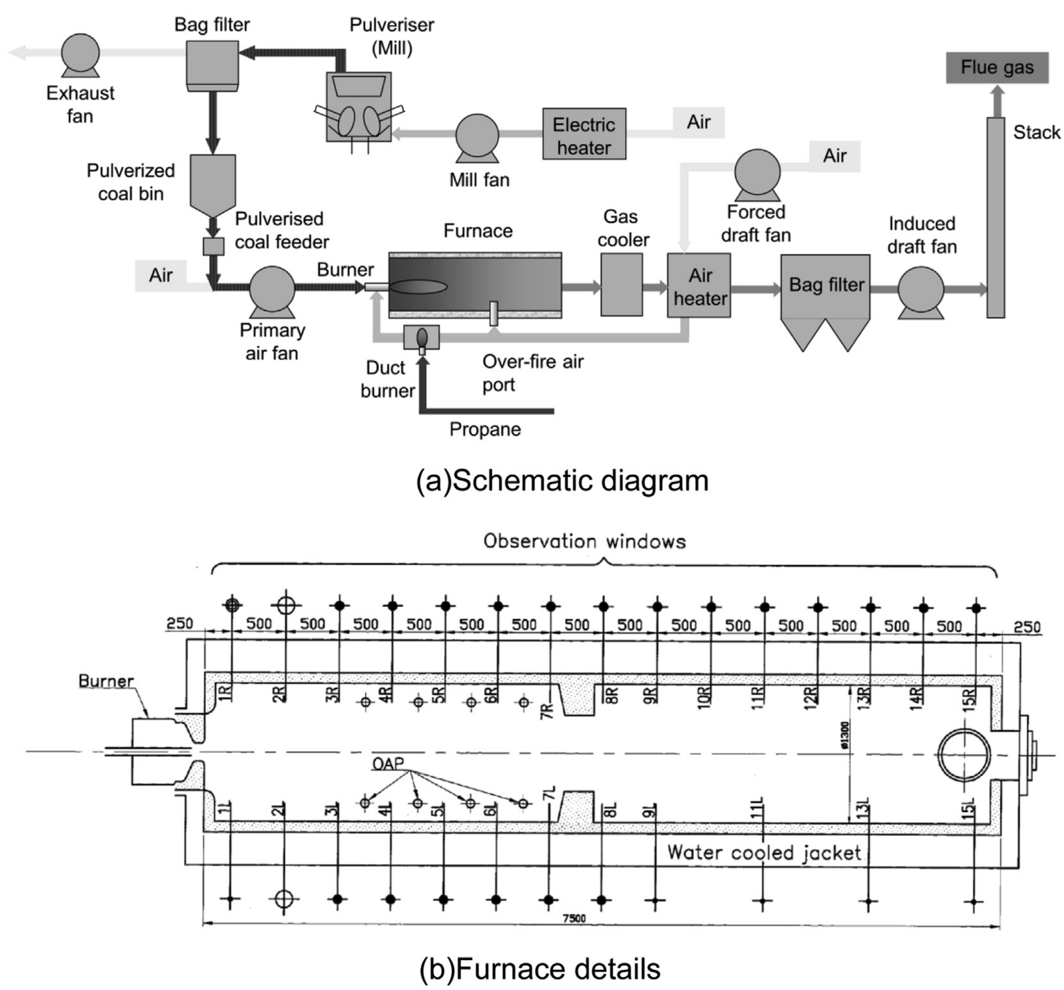


Fig. 1. Experimental facility (1.2 MWth).

Table 1
Tested coal properties.

Items	Unit	Bituminous coal	Bituminous coal	Bituminous coal
		Hunter valley-A	Hunter valley-B	Mount Owen
Calorific value (HHV)	MJ/kg-dry	29.6	28.5	29.2
Total moisture	wt%-as received	6.1	6.7	8.6
Proximate analysis				
Moisture	wt%-air dry	1.8	2.3	2.4
Ash	wt%-dry	12.9	8.8	14.4
Volatile matter	wt%-dry	31.0	34.4	32.4
Fixed carbon	wt%-dry	56.1	56.8	53.2
Elemental analysis				
C	wt%-dry	71.6	70.0	70.6
H	wt%-dry	5.00	4.6	4.74
N	wt%-dry	1.82	1.2	1.36
O	wt%-dry	8.13	14.9	8.35
S	wt%-dry	0.55	0.47	0.55

through over-fire air ports (OAP) at four stations located 1.5, 2.0, 2.5 and 3.0 m away from the burner exit; at each of these stations three ports are arranged circumferentially. Residence time in the primary combustion zone can be changed by the selection of OAP stage. The installed vertical roller mill grinds coal into a pulverised coal with 80% being able to pass through a 75 μm sieve size. Pulverised coal is fed through a gravimetric table feeder to an indirect firing system. In the actual boiler, hot flue gas will be extracted from the heat recovery area and mixed with the combustion air. To resemble the actual situation, a combustible mixture of low oxygen concentration is produced by using a duct burner with propane gas firing. The duct burner produces NO_x, which generally influences the flue gas NO_x emissions. Previously Kimura et al. [18] evaluated the NO_x decomposition characteristics in the firing of oil, gas and pulverised coal with low oxygen combustible mixture. The firing process was assumed to be the re-powering a boiler with a gas turbine. The results showed that the NO_x decomposition in coal-fired staged combustion reached 90%. In this research the NO_x produced from the duct burner firing is less than 20 ppm and, thus, its influence can be neglected.

NO_x, SO_2, O_2, CO in flue gas and wind box O_2 and NO_x are continuously analysed. Combustion residue is sampled and its ash content analysed based on JIS (Japanese Industrial Standards) M8812-2004. The sample is burnt in an electrically heated furnace at 815 ± 10 °C for more than 1 h. The weight loss through this procedure is assumed to be attributed to the combustion of unburnt carbon. Australian bituminous coals are used with properties as shown in Table 1.

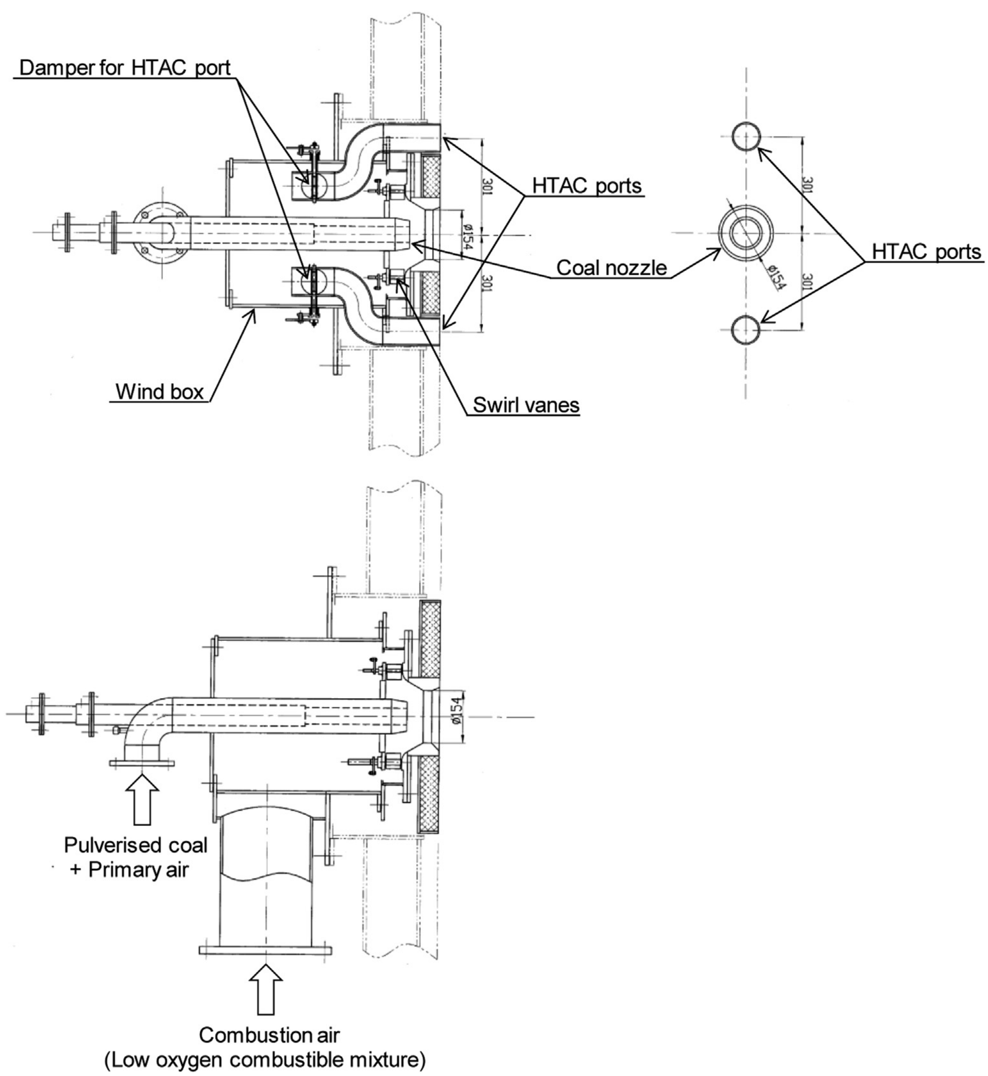


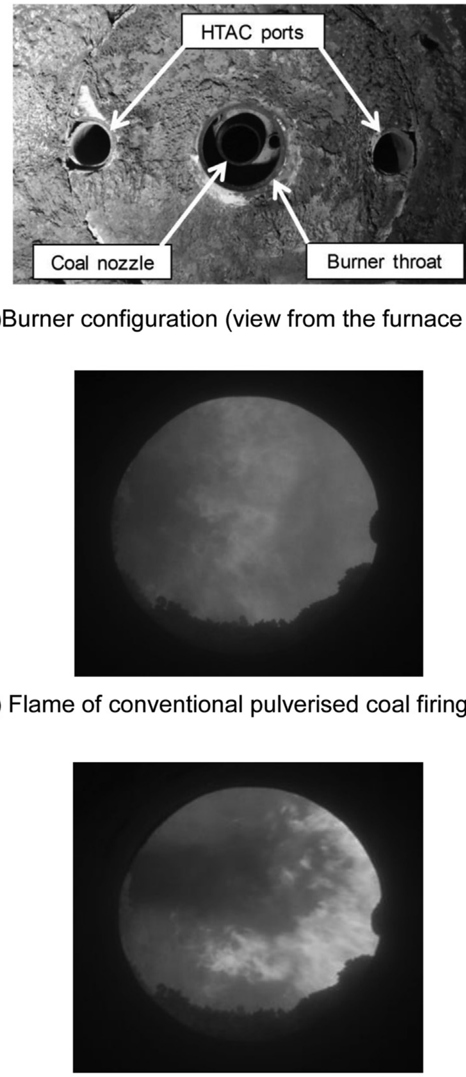
Fig. 2. Proposed HTAC burner which can achieve conventional firing as well as HTAC.

2.2. Burner for conventional and HTAC modes

The pulverised coal burner is designed for achieving both, conventional and HTAC modes. There does exist a number of studies regarding HTAC at air temperature exceeding 800 °C [4–17]. Various types of regenerators are used with switching times in the order of tens of seconds. As mentioned in the introduction, this switching is difficult to apply to pulverised coal firing, because the suspension of the coal supply, the valve switching and restart of coal supply take time and cause a repeated lack of coal supply. However, continuous firing is required for pulverised coal in HTAC. The wall of the firing burner, proposed here, has vanes for generating swirl flow air for combustion. When the vanes close completely, the air flow can be cut off. Fig. 2 shows the proposed configuration of HTAC burner. A combustible mixture can be supplied from the other hole(s) separated from the coal jet when the swirl vanes are fully closed. Orsino et al. [19] carried out HTAC experiments with pulverised coal. In these experiments an air channel was located at the centre and the combustible flue gas mixture was injected with a velocity of ~65 m/s. Two coal nozzles were located at three different distances from the centre air, 175, 280 and 385 mm. The farthest nozzle position of 385 mm showed lowest NO_x emissions and higher burnout at the same time. The HTAC burner used in this study was designed with reference to these configurations.

2.3. Experimental conditions

The firing experiments are performed for conventional and HTAC conditions. The relatively low temperature of air (185 °C) is supplied to the conventional configuration and those results are compared with the HTAC results. From the experiences with conventional firing of pulverised coal, it was observed that the coal flame became unstable with a combustion air temperature lower than 180 °C; thus, the combustion air temperature is set to 185 °C. The main experimental parameters are the wind box oxygen concentration, temperature and OAP location. The target experimental conditions are shown in Table 2. Characteristics such as flue gas oxygen and NO_x are also examined when changing the firing mode. After establishment of the conventional firing and warming up of the furnace, the firing mode is changed from conventional to HTAC by gradually opening the HTAC ports. After the flame stability is confirmed, the swirl vanes are closed completely.



(a)Burner configuration (view from the furnace inside)

(b) Flame of conventional pulverised coal firing

(c) Flame of HTAC mode

Fig. 3. Visual flame viewing from the observation port of furnace.

3. Results and discussion

3.1. Flame stability in HTAC mode and during mode switching

Many researchers have carried out and evaluated experiments related to HTAC; however, there are no studies where burner operation in actual boilers is considered. In this study, the possibility of using HTAC mode with a relatively low temperature of 185 °C was observed. Fig. 3 shows the visual flames of conventional and HTAC modes. It was observed that both modes show stable ignition and firing for Hunter valley as well as Mount Owen coals. In the conventional mode, the bright orange flame was situated at the burner throat and a very short coal jet was observed. In HTAC mode, there was a black coal jet without any visible flame close to the throat. The coal jet length was ~500 mm long; an orange bright flame started from downstream of the black coal jet. The time histories of flue gas O_2 and NO_x for both types of coal are shown in Fig. 4. Since the O_2 concentration is stable, it can be concluded that the combustion maintains stable condition during and after changing the firing mode. This result suggests that the HTAC application has a high reliability when used in pulverised coal fired boilers.

Table 2
Operational conditions of conventional and HTAC.

Operation parameters	Unit	Conventional	HTAC
Firing rate	kg/h	100	100
Flue gas O_2	vol.%-dry	3.5	3.5
Air staging	%	20	20
Primary air flow	kg/h	180	180
Combustion air temperature	deg-C	185	185, 480
Wind box O_2	%-dry	21	17.5

3.2. NO_x and unburnt carbon in HTAC mode

Comparing the results with that of conventional firing, NO_x emissions are reduced in HTAC under all conditions as shown in Figs. 4 and 5(a). Variation of NO_x emission when changing the distance between burner exit and OAP was the same for both conventional and HTAC modes. A longer distance leads to longer residence time in the sub-stoichiometric zone, which results in

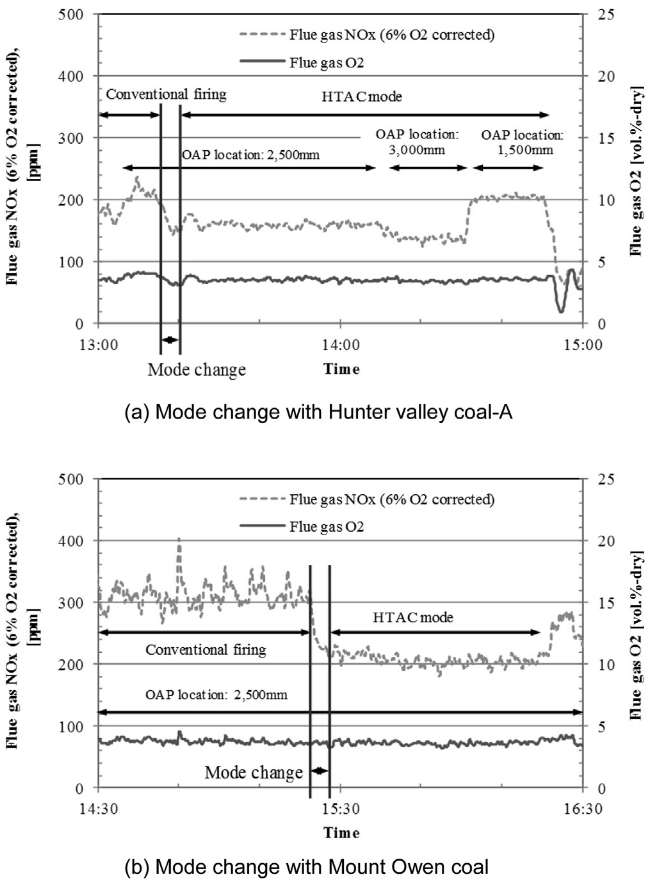


Fig. 4. Gas concentrations in flue gas during change from conventional firing to HTAC mode.

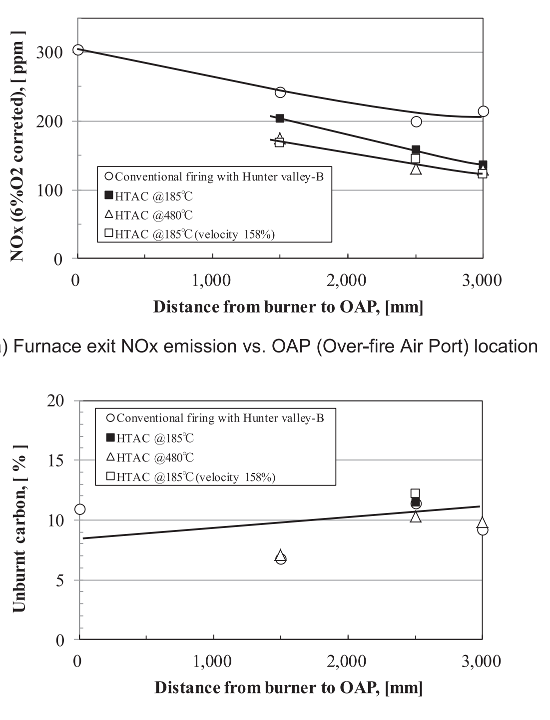


Fig. 5. Emission performance with conventional firing and HTAC mode for Hunter valley coal-A.

lower NO_x emission. Unburnt carbon levels of conventional and HTAC modes maintain the same level of ~10% (Fig. 5(b)). It was also observed that the variation of combustible mixture temperature had almost no effect on burnout.

Fig. 6 shows the effect of flue gas O_2 concentration on unburnt carbon content and NO_x emission with an air staging ratio of 20% and OAP at 2500 mm. These trends were found to be the same for both modes. With increasing flue gas O_2, NO_x is increased and unburnt carbon is reduced. This shows that HTAC mode has a better performance compared to conventional firing, i.e. lower NO_x and lower unburnt carbon.

3.3. Temperature profile

It was expected that HTAC would produce a flat temperature profile due to slow combustion, which results in a uniform metal temperature, avoiding hot spots on the furnace wall. The combustion air supplied from the HTAC ports at a speed of 65 m/s, expands and builds large recirculation areas. The coal jet then enters into this recirculation zone. The characteristics of HTAC are that the oxidation reaction is slow and stable, and the environmental is at elevated temperatures with a low concentration of oxygen. Flame temperature along the furnace axis is measured by an infrared radiation thermometer through the observation ports (Fig. 7). The temperature profiles of HTAC mode became flat and uniform in comparison with that of conventional firing. In the case of HTAC, the mixing of fuel and combustible mixture is slow, which causes the combustion to take place in the whole furnace. Thus, the flat and uniform temperature profile can be realised. When increasing

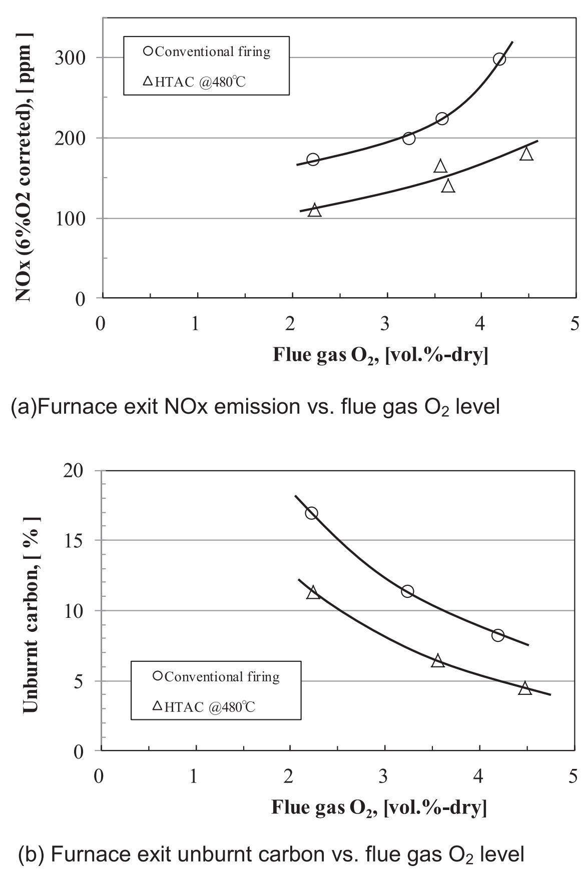


Fig. 6. Emission performance with conventional firing and HTAC mode for Hunter valley coal-B.

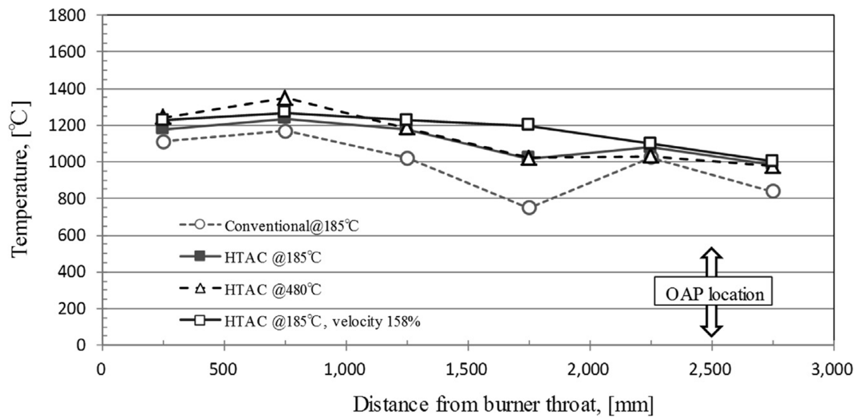


Fig. 7. Flame temperature profile for different firing modes for Hunter valley coal-A.

the velocity of combustible mixture, this tendency becomes more pronounced.

4. Conclusions

From the combustion experiments with a novel burner, the following conclusions are drawn:

1. The proposed burner can realise both conventional firing and HTAC mode. Changing from conventional to HTAC mode, which is particularly important for cold start, can be smoothly achieved without any unstable operation.
2. Even with a combustion air temperature as low as 185 °C, HTAC can be achieved with high firing performance.
3. The combustion behaviour under HTAC mode shows the same tendency as conventional firing. NO_x can be reduced with longer residence time in the sub-stoichiometric zone under staged combustion. NO_x and unburnt carbon show inverse trends with varying flue gas O_2 level.

From the above results, this study confirms that HTAC technology can be realised in the utility pulverised coal fired boilers.

Acknowledgements

The authors wish to acknowledge the assistance of the furnace operators who have substantially contributed to this research work.

References

[1] H. Spliethoff, U. Greul, H. Rüdiger, R.G. Hein Klaus, Basic effects on NO_x emissions in air staging and reburning at a bench-scale test facility, Fuel 75 (5) (1996) 560–564.
[2] A. Ribeirete, M. Costa, Impact of the air staging on the performance of a pulverized coal fired furnace, Proc. Combust. Inst. 32 (2009) 2667–2673.
[3] J. Yang, R. Sun, S. Sun, N. Zhao, N. Hao, H. Chen, Y. Wang, H. Guo, J. Meng, Experimental study on NO_x reduction from staging combustion of high volatile pulverized coals. Part 1. Air staging, Fuel Process. Technol. 126 (2014) 266–275.
[4] D. Hardesty, F. Weinberg, Burners producing large excess enthalpies, Combust. Sci.. Technol. 8 (1974) 201–214.
[5] J.A. Wünning, J.G. Wünning, Flameless oxidation to reduce thermal NO-formation, Prog. Energy Combust. Sci. 23 (1997) 81–94.
[6] A. Cavaliere, M. de Joannon, Mild combustion, Prog. Energy Combust. Sci. 30 (2004) 329–366.
[7] J. Haas, M. Tamura, NO_x reduction in oil fired glass tanks: experiments and simulations, J. Energy Inst. 84 (3) (2011) 146–154.
[8] T. Hasegawa, S. Mochida, Development of advanced industrial furnace using highly preheated combustion air, J. Propuls. Power 18 (2) (2002) 233–239.
[9] D. Szewczyk, P. Skotnicki, HiTAC technology combined with HRS burners in a walking beam steel reheating furnace, in: 8th Int. Symposium on High Temperature Air Combustion and Gasification, Jul. 5–7, 2010. Poland.
[10] A. Giese, U. Konold, H.A. Al-Halbouni, H.K. Görner, G. Schwarz, B. Köster, Application of flameless oxidation in glass melting furnaces GlasFLOX, in: 7th Int. Symposium on High Temperature Air Combustion and Gasification, Jan. 13–16, 2008. Thailand.
[11] M. Katsuki, T. Hasegawa, The science and technology of combustion in highly preheated air, in: 27th Symposium (Int.) on Combustion, The Combustion Institute, Pittsburgh, 1998, pp. 3135–3146.
[12] T. Suda, M. Takafuji, T. Hirata, M. Yoshino, J. Sato, A study of combustion behaviour of pulverized coal in high-temperature air, Proc. Combust. Inst. 29 (2002) 503–509.
[13] T. Kiga, K. Yoshikawa, M. Sakai, S. Mochida, Characteristics of pulverized coal combustion in high-temperature preheated air, J. Propuls. Power 16 (4) (2000) 601–605.
[14] R. Weber, J.P. Smart, W. vd Kamp, On the (MILD) combustion of gaseous, liquid, and solid fuels in high temperature preheated air, Proc. Combust. Inst. 30 (2005) 2623–2629.
[15] P. Li, F. Wang, Y. Tu, Z. Mei, J. Zhang, Y. Zheng, H. Liu, Z. Liu, J. Mi, C. Zheng, Moderate or intense low-oxygen dilution oxy-combustion characteristics of light-oil and pulverized coal in a pilot-scale furnace, Energy Fuels (2014).
[16] H. Stadler, D. Ristic, M. Förster, A. Schuster, R. Kneer, G. Scheffknecht, NO_x-emissions from flameless coal combustion in air, Ar/O_2 and CO_2/O_2, Proc. Combust. Inst. 32 (2009) 3131–3138.
[17] N. Schaffel-Macini, M. macini, A. Azlek, R. Weber, Novel conceptual design of a supercritical pulverised coal boiler utilizing high temperature air combustion (HTAC) technology, Energy 35 (2010) 2752–2760.
[18] K. Kimura, T. Kiga, M. Tamura, S. Miyamae, M. Ozawa, Characteristics of NO_x decomposition in firing process of a boiler with fully fired combined cycle, in: Proc. JSME-ASME International Conference on Power Engineering, 93, 1993, pp. 487–492.
[19] S. Orsino, M. Tamura, P. Stabat, S. Costantini, O. Prado, R. Weber, Excess Enthalpy Combustion of Coal Results of High Temperature Air Combustion Trials HTAC99, IFRF Doc. No. F46/y/3, 2000.